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SILICON INGOT CASTING - HEAT EXCHANGER METHOD MULTI-WIRE SLICING - FIXED ABRASIVE SLICING TECHNIQUE

Phase III

Silicon Sheet Growth Development for the
Large Area Sheet Task of the Low-Cost Solar Array Project

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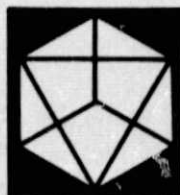
BY

FREDERICK SCHMID AND CHANDRA P. KHATTAK

Covering Period from December 15 through December 31, 1978

Report Issued: January 1979

JPL Contract No. 954373



CRYSTAL SYSTEMS INC.

Shoeland Industrial Park, 35 Congress Street, Salem, Mass. 01970

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ABSTRACT

This contract covers two areas -- silicon ingot casting by Heat Exchanger Method (HEM) and multi-wire slicing by the Fixed Abrasive Slicing Technique (FAST). Phase II of this program has just been completed.

In the area of ingot casting the proof of concept of HEM was established in Phase I. During Phase II it was established that HEM cast silicon yields solar cell performance comparable to Czochralski grown material. Solar cells with conversion efficiencies of up to 15% have been fabricated. In addition it has been shown that square cross-section ingots can be cast. During Phase III of the program it is intended to scale-up the process.

In the area of crystal slicing during Phase I it was established that silicon can be sliced efficiently with the FAST approach. This concept was carried forward to 10 cm diameter workpiece during Phase II. It is intended to demonstrate during Phase III that 10 cm x 10 cm cross-section silicon ingots can be sliced to achieve 25 wafers per cm with minimum kerf.

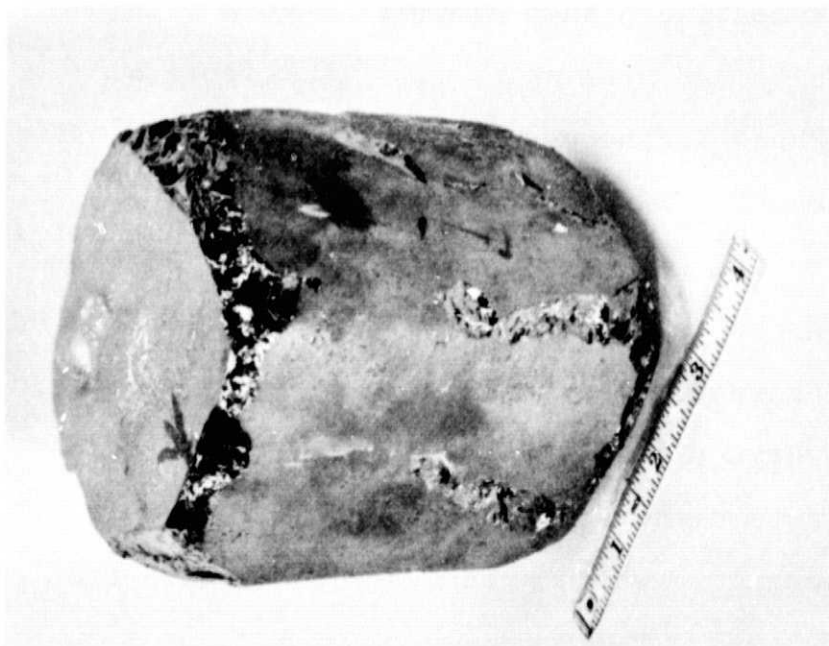
SILICON INGOT CASTING - HEAT EXCHANGER METHOD

The Phase II of the contract ended on December 1, 1978. Since then a one-year Phase III has been negotiated to scale up HEM. In order to exhibit continuity of the program, the salient features of Phase II will be summarized followed by the technical goals of Phase III.

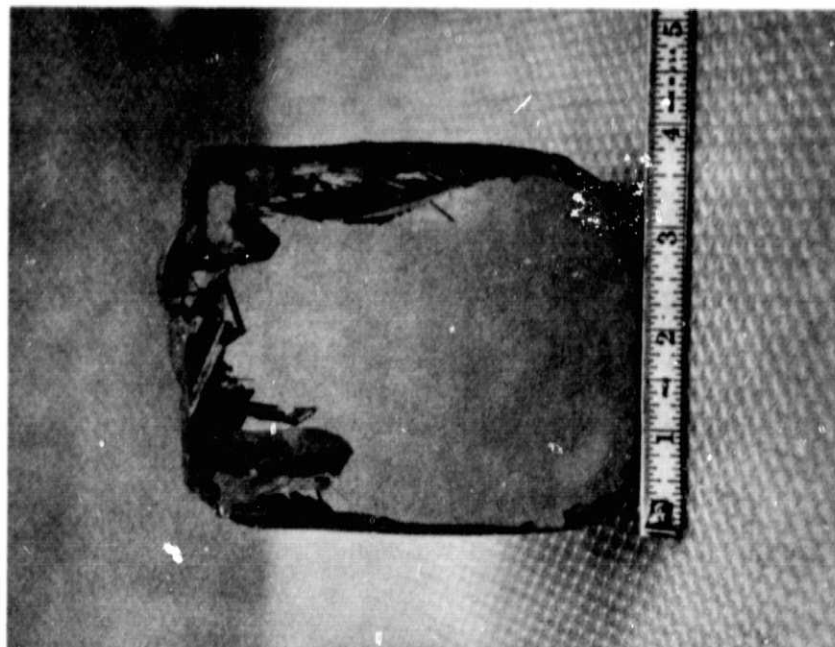
Summary of Progress for Phase II

It has been demonstrated¹ that the Heat Exchanger Method (HEM) produces silicon by a low-cost process without compromising the quality of the material for photovoltaic applications. This was shown by casting 6-inch diameter ingots with over 90% single crystallinity and high solar cell efficiencies.

During the Phase II the process was extended to casting of square cross-section ingots. Reduction in costs due to higher cell-packing density are clearly evident. Figure 1 shows a crackfree square cross-section ingot cast by the HEM. A polished and etched cross-section of this ingot exhibiting a high degree of crystallinity is also shown. It is clear that flowing of melt into corners was not a problem. HEM is, therefore, the only technique which produces square cross-section



(a)



(b)

Figure 1. (a) Square cross-section ingot cast in run 2-081-C; (b) A polished and etched section of this ingot.

ingots with a high degree of single crystallinity.

The source of SiC impurities during vacuum melting of silicon has been identified with the use of graphite retainers in contact with silica crucibles.¹ At the melting point of silicon these reactions become operative below about 30 torr and can be prevented by using molybdenum retainers. This has been confirmed experimentally by reducing the carbon content from a saturation level in silicon to about 50%.² SiC floating on the surface of the melt were nucleation sites for spurious growth. Therefore, the use of molybdenum retainers has reduced the carbon levels as well as improved crystallinity of cast silicon. Operation in vacuum omits the cost of high-purity argon as well as reduces the oxygen content of silicon. Typical oxygen analysis of HEM cast silicon³ were $(4-11) \times 10^{17}$ atoms/cc, compared to about 26×10^{17} atoms/cc reported in Czochralski grown silicon.

Solar cells fabricated from HEM cast silicon have shown conversion efficiencies of up to 15% (AM1). Typical solar performance on 2 cm x 2 cm size cells from one ingot are shown in Table I. This solar cell performance is already comparable to the production cells from Czochralski silicon. These cells have been fabricated without optimization of material or cell processing parameters, and the graphite parts used in the HEM furnace were not purified.³ It is felt that operation in vacuum minimizes the effect of volatile impurities.

TABLE I

SOLAR CELL PERFORMANCE OF 2 cm x 2 cm CELLS
HEM CAST SILICON (RUN 2-049-C)

Cell No.	AMO I_{sc} (mA)	AMO V_{oc} (mV)	AMO η	CFF	AM1 η
1	148	583	12.2	0.77	14.2
2	156	591	12.8	0.75	15.0
3	156	587	11.6	0.69	13.5
4	156	587	12.5	0.74	14.6
5	157	591	12.4	0.72	14.5
6	148	577	11.5	0.73	13.4
7	149	533	12.0	0.75	14.0

Conclusions

- : Square cross-section ingots have been cast by HEM with a high degree of crystallinity.
- : Molybdenum retainers have reduced the carbon content of HEM cast silicon by 50%.
- : The absence of SiC on the surface of the melt has improved crystallinity of cast silicon.
- : The oxygen content of HEM cast silicon is lower than typical Czochralski grown silicon.
- : Thermodynamic analysis has shown that it is possible to process silicon in vacuum. This was experimentally confirmed.
- : Solar cells fabricated from HEM cast silicon have shown up to 15% (AM1) conversion efficiency.
- : This cell performance has been achieved in spite of using a contaminated furnace and unpurified graphite parts.

Milestones for Phase II

<u>Technical Goals</u>	<u>Status</u>	<u>Remarks</u>
Size - 2.5 kg	Surpassed	3.3 kg
Shape - square cross-section	Completed	
Growth rate - 1 kg/hr	Surpassed	1.2 kg/hr
Dislocation density - $<10^4/\text{cm}^2$	Surpassed	$100/\text{cm}^2$
Crystallinity - 75%	Surpassed	>90%
Solar cells - 10% η	Surpassed	15% η

Technical Goals for Phase III

It has been established that the HEM produces silicon crystals at low cost without compromising the quality of the silicon for photovoltaic applications. It is now intended to extend the process from the development to the prototype production stage. Major emphasis during Phase III will be on scale-up in size of cast ingots. High array-packing density is important to reduce cost; hence it is intended to cast 20 x 20 cm cross-section ingots weighing 18.5 kg. A solidification rate in excess of 1 kg/hr is expected. Other goals are dislocation density of less than 10^4 cm^{-2} and single crystallinity greater than 90% by volume and solar cell conversion efficiency greater than 12% (AM1).

MULTI-WIRE SLICING--FIXED ABRASIVE SLICING TECHNIQUE

Under Phase II of the slicing program, the technical feasibility for economically slicing 10 cm diameter ingots by FAST has been demonstrated. Emphasis in Phase III will be to further develop the process. A summary of the Phase II achievement is presented followed by the goals for Phase III.

Summary of Progress for Phase II

Multi-wire Fixed Abrasive Slicing Technique (FAST) has the combination of advantages of other slicing techniques, viz., low expendable material costs of ID technology, low labor and capital of multiblade slurry slicing and high material utilization of multi-wire slurry technique. However, FAST has been in an infancy stage of development. The proof of concept of this method was established¹ with a machine designed for multiblade slurry slicing. Based on the experience with a modified slurry machine a one-of-a-kind high speed slicer based on new concepts was designed, fabricated, assembled and tested.

All the parameters for economic slicing such as low kerf, thin slices, low expendable materials, etc., had been demonstrated for 4 cm x 4 cm workpieces. Large workpieces could not be sliced with the modified slurry machine. Initial slicing of 7.6 cm and

10 cm diameter workpieces with the high speed slicer gave 97% yield. These tests also proved that blades will give better performance when used at higher speeds.

The high speed slicer, as shown in Figure 2, is a basic experimental machine which could be modified, if necessary. The essential features are that it has a larger and lighter carriage so that higher speeds and longer stroke can be achieved. The wire carriage is an aluminum weldment that is reciprocated on air bearings. The carriage is moved back and forth by a link guided by a straight line motion mechanism which is crank actuated. By shifting the crank pin location on the guide mechanism, different stroke lengths can be obtained. Beneath the guide mechanism is a second crank which has a mass equal to the carriage weight attached to its end. This crank is driven out of phase with the carriage motion, and thus serves to damp the inertial loads of the system. In production model, another carriage will replace the equal mass so two carriages will be driven by one drive system.

During slicing tests with the high speed slicer very good vibrations isolation was obtained as the drive assembly is mounted separately from the machine frame. A view of the slicer after slicing a 10 cm diameter silicon ingot is shown in Figure 3.

In the area of blade development it was found that kerf can be controlled to a low value when diamonds are impregnated

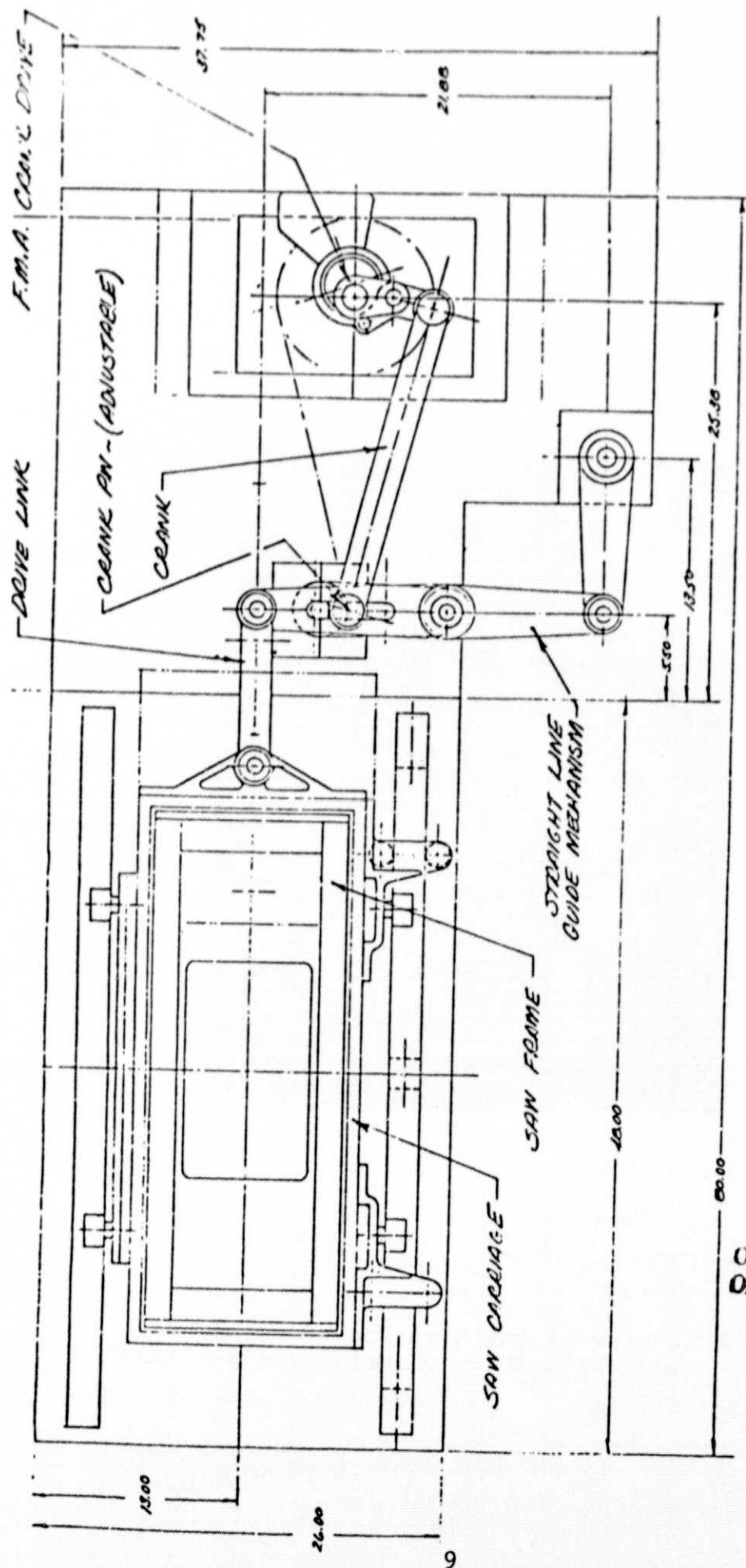


Figure 2. Crystal Slicer - Plan View

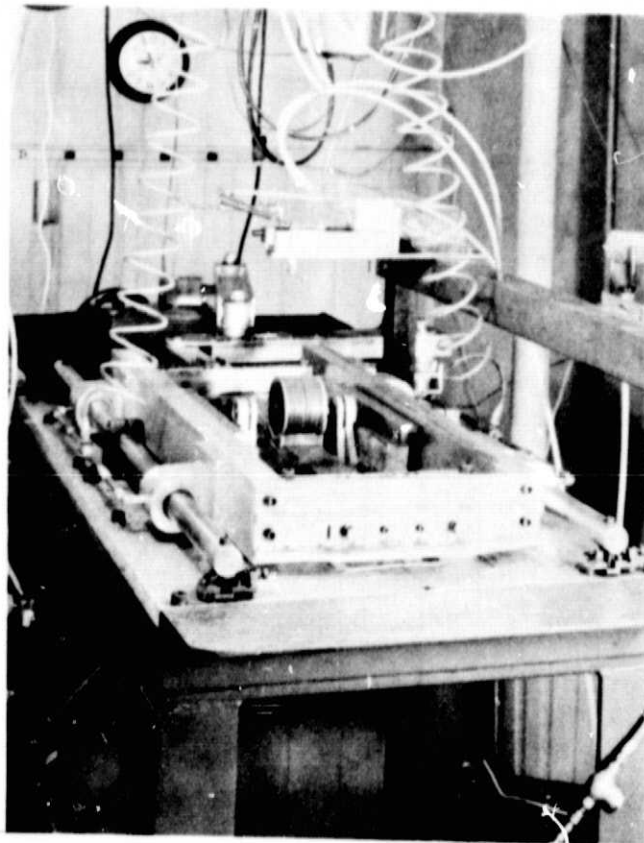


Figure 3. A view of the high-speed slicer after slicing a 10 cm diameter silicon ingot

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in the cutting edge only. Slicing with these wires has shown higher yields (92-100%) than commercially impregnated wires.³ The high yields are due to low kerf and good accuracy. One significant factor which contributes to the accuracy is that the wires do not have diamonds on the top surfaces; hence, they seat well in the grooved rollers, thereby reducing wander. Under these conditions the rollers are not degraded also.

Conclusions

- : The high speed slicer has been fabricated and slicing tests carried out.
- : Initial slicing with 7.6 cm and 10 cm diameter silicon gave 97% yield.
- : It has been established that wire blades with fixed diamond perform better at higher speeds.
- : Technology to impregnate diamonds only in the cutting edge has been demonstrated.
- : Higher yields (92-100%) have been obtained with CSI impregnated wires as compared to commercially impregnated wires.
- : Higher yields are associated with lower kerf and reduced wander.

Program Status for Phase II

<u>Technical Goals</u>	<u>Status</u>	<u>Remarks</u>
Design and fabricate new slicer	Completed	
Workpiece size - 10 cm diameter	Completed	
Slice thickness - 0.010 to 0.025 cm	Completed	
Slicing rate - 0.01 to 0.025 cm/min	Completed	
Kerf length - 10 cm	Completed	
Kerf width - 0.020 cm	Surpassed	0.016 cm
Parallel slices - 200	-	132

Technical Goals for Phase III

In the FAST program, at the end of Phase II the elements necessary to slice efficiently have been demonstrated; however, the combinations of all elements together is the goal for Phase III. For example, it has been demonstrated that 25 wafers/cm of ingot with kerf as low as 160 μm can be achieved but this has been shown on 4 cm x 4 cm sections. As another essential ingredient the slicing of 10 cm diameter silicon has also been carried out. At the end of Phase III, therefore, it is intended to produce 25 wafers per linear cm of 10 cm diameter or 10 cm x 10 cm cross-section silicon with a kerf width of less than 175 μm , slice thickness greater than 225 μm and a yield of over 95%. It is expected to achieve these goals with the combination of machine development, blade development and testing program.

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